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GB 1557484 A   GB 1516427 A   US 3995937 A

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(54) **Electrically controllable grating**

(57) An electrically controllable grating 6 is provided by forming regions 4 of different refractive index within an electro-optic material 2. Electrodes 10 and 12 are provided so that a readily controllable electric field gradient may be applied to the index grating formed by the alternating regions such that the refractive index of the regions may be varied electrically to form a controllable grating. The grating 6 may be used as an electrically controllable distributed Bragg reflector to allow variable wavelength feedback within a laser cavity. The grating may be used to perform wavelength division multiplexing and/or frequency modulation.

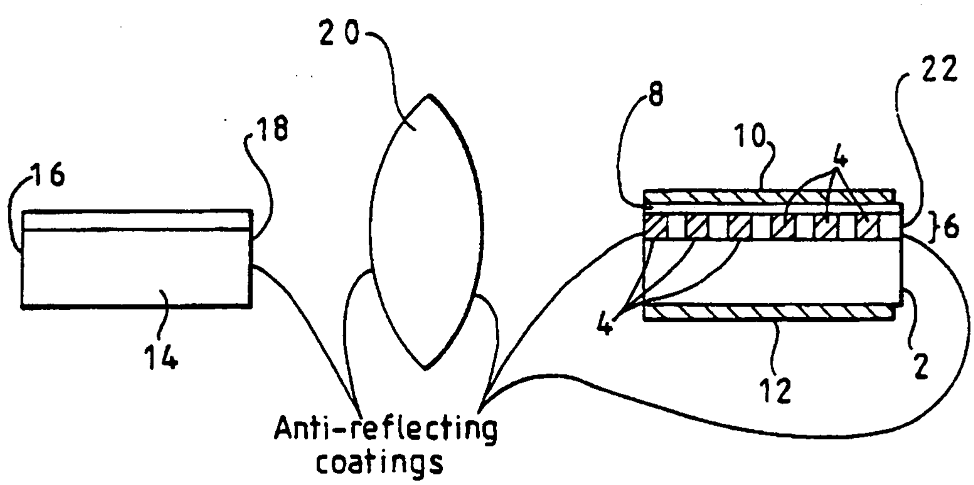


FIG 2

GB 2 286 057 A

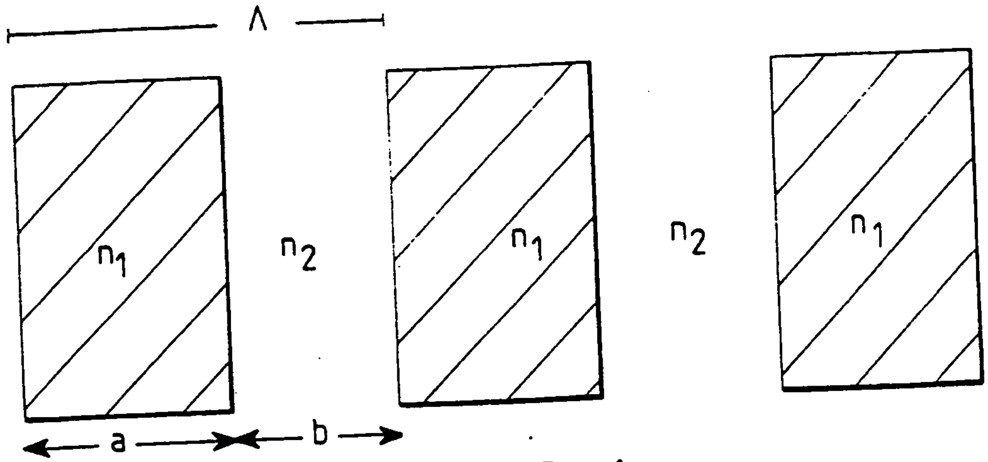

Λ
n_1
n_2
n_1
n_2
n_1
a
b

FIG 1

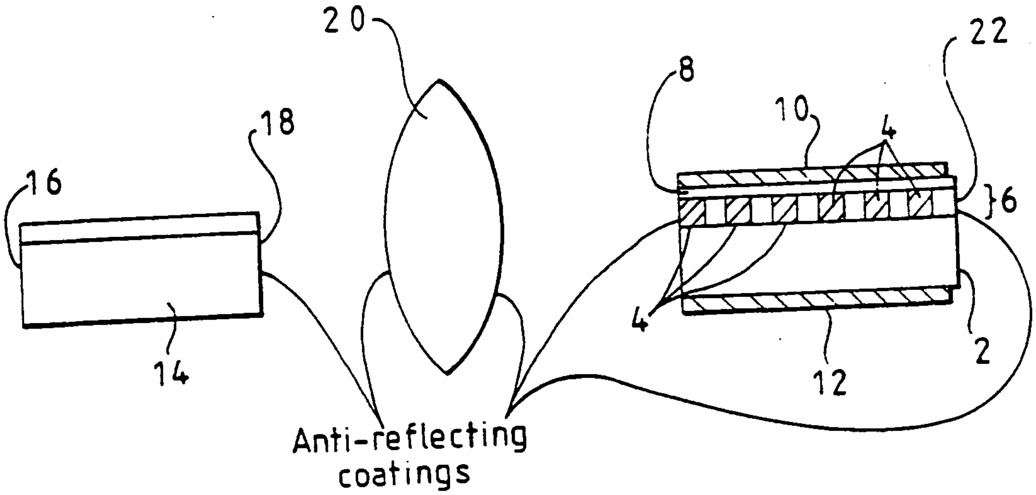

20
22
8
10
4
}6
18
16
14
4
12
2
Anti-reflecting coatings

FIG 2

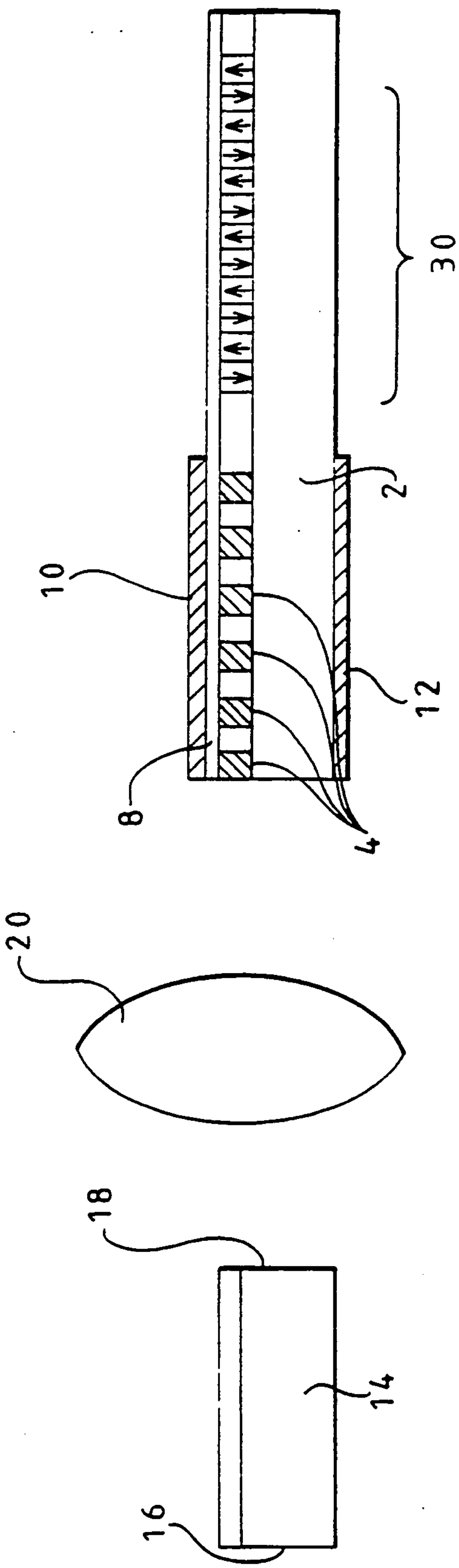
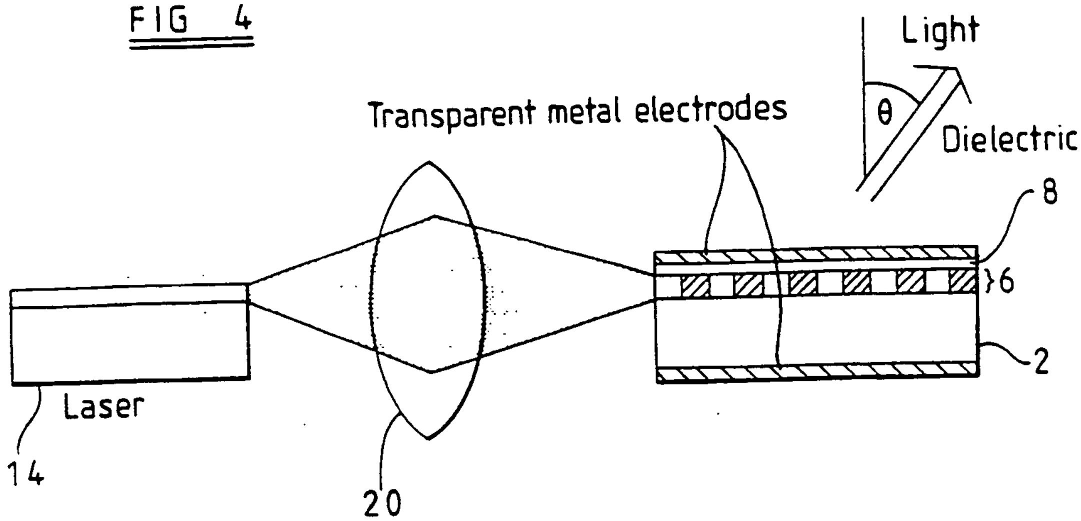


FIG 3

FIG 4


Light
θ
Dielectric
Transparent metal electrodes
8
6
2
Laser
14
20

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ELECTRICALLY CONTROLLABLE GRATING

The present invention relates to an electrically controllable grating. Such a grating is suitable for controlling the wavelength of laser light.

It is known to use interdigitated electrodes on electro-optic materials, where application of an electric field causes the formation of a modulating grating within the electro-optic material. The grating can be switched on and off, and may be used to provide beam steering.

According to the present invention, there is provided an electrically controllable grating comprising an electro-optic material having a first region forming a refractive index grating, and means for applying an electric field to the refractive index grating for controlling the refractive index of the electro-optic material.

It is thus possible to vary the refractive index of the material of the refractive index grating and thereby to vary the effective pitch of the grating.

Preferably the means for applying an electric field is arranged to apply an electric field having a component transverse to the refractive index grating.

Preferably first and second electrodes are disposed adjacent the first region for applying an electric field to the first region.

Advantageously the grating may be included within a laser cavity and be

arranged to act as a retro-reflecting grating so as to provide a wavelength controllable laser. The grating may be controlled with a direct current (DC) voltage to perform frequency control suitable for use, for example, in a frequency division multiplexed system. Additionally or alternatively, an alternating voltage, superimposed on a DC voltage (including zero volts) may be applied to the grating to perform frequency multiplexing of the laser.

A plurality of gratings may be provided in parallel so as to enable parallel multiplexing of the laser. Parallel gratings may be formed by provision of segmented electrodes such that a spatially varying electric field may be applied to the first region. A plurality of lasers may be formed as an array to provide a wavelength division multiplexed light source.

Advantageously the or each laser may further comprise a phase modulator.

Advantageously a grating may be formed in series with at least one optical element on a shared substrate.

Advantageously a grating may be formed in series with a second harmonic generator in order to provide a second harmonic generator which may be electrically controlled to be temperature compensated over a predetermined temperature range.

The grating may advantageously be used as a tunable filter for transmitter and/or receiver elements within an optical communications system.

Furthermore, the grating may be arranged as a surface emitting grating in

which the angle of emission is electrically controllable.

The present invention will further be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic diagram of part of a refractive index grating;

Figure 2 is a schematic diagram of a laser having an electrically controllable grating constituting an embodiment of the present invention;

Figure 3 is a schematic diagram of a laser having a second harmonic generator and an electrically controllable grating constituting an embodiment of the present invention; and

Figure 4 is a schematic diagram of an electrically controllable surface emitting grating constituting an embodiment of the present invention.

The electro-optic effect gives rise to a change in refractive index of a material when an electric field is applied to the material. The size of the change in refractive index may be easily estimated for a given crystal having a given orientation. For z-cut lithium niobate, the largest electro-optic coefficient is r_{33} whose magnitude is 31 pm/V. The change of refractive index (Δn) for a field applied along the z direction is:

$$\Delta n = -n_e^3 . r_{33} . V/2t \qquad (1)$$

Where:

n_e is the refractive index;
t is the thickness of the crystal;
V is applied voltage; and
r_{33} is a coefficient.

The above equation estimates the change in refractive index that is experienced by light propagating along the xy plane with a linear polarisation parallel to the z direction. Thus for a field of 2×10^7 V/m, equivalent to 1000V across a wafer 50 microns thick, (higher fields may lead to depoling) and $n_e=2.2$, then the change in refractive index is $\Delta n=0.0033$.

A refractive index grating may be formed by an alternating pattern of regions of a first refractive index having neighbouring regions of a second refractive index. Such a periodic variation in refractive index can be used as a distributed Bragg reflector. The properties of distributed Bragg reflectors have been reported by W.P.Risk and S.D.Lau, "Distributed-Bragg-reflection properties of segmented KTP waveguides", Optics letters, Vol 18, No 4, Feb 1993,p272-274 and by K. Shinozaki, T. Fukunaga, K. Watanabe, and T. Kamijah, "Self-quasi-phase-matched second-harmonic generation in the proton-exchanged $LiN6O_3$ optical waveguide with periodically domain-inverted regions", APL vol 59 1991.

For the structure illustrated in Figure 1, in which n_1 is a region having a first refractive index and n_2 is a region having a second refractive index, strong Bragg reflection is obtained when

$$(m\ \lambda_m)/(2\ n_{eff}) = \Lambda \qquad (2)$$

where:

- m is an integer greater than zero and represents the order of the reflection;
- λ_m is the wavelength of the mth order;
- n_{eff} is the effective refractive index; and
- Λ is the spatial period of the reflector (equal to a+b).

To a good approximation, n_{eff} can be found from:

$$n_{eff} = (n_1 a + n_2 b)/(a+b) \qquad (3)$$

Thus reflection gratings using Bragg reflection can be designed to be strongly reflecting at a predetermined wavelength.

For a reflection grating having a maximum reflection at approximately 800nm, the variation of refractive index using the Z-cut lithium niobate as described above gives a variation in reflection wavelength over a range of 1.2nm. Reversal of the polarity of the electric field with respect to the crystal would increase the total tunable range (which may also be known as bandwidth) to 2.4nm. The same bandwidth is possible at a peak reflectivity of approximately 1500nm with substantially half the applied voltage. The line width of the reflection peak ,i.e. its pass band, is an important factor which is dependent upon the sharpness and the shape of the grating, its periodicity, its accuracy, the difference in refractive index between the first and second regions and the length of the grating. For a given length, a first order grating has a narrower line width than a higher order grating, although the first order grating is generally more difficult to fabricate since smaller structures have to be formed. For a first order grating, line widths of the order of those produced by distributed feedback lasers are achievable, for example, 10MHz which is equivalent to a line width of less than 0.001 Angstroms at a wavelength of 1500nm. For operation using higher orders, a line width of approximately 10GHz (less than 1 Angstrom) at 1500nm is achievable. The ability to provide decreased line width becomes important for use in systems employing coherent communication schemes, whereas the larger line widths are suitable for use in direct detection wavelength division multiplexing systems and applications

involving phase matched non-linear interactions.

The apparatus illustrated in Figure 2 comprises a wafer 2 of z-cut lithium niobate having a plurality of proton exchanged regions 4 arranged in a regular array. The proton exchanged regions 4 have a higher refractive index which is typically 0.1 larger than the non-exchanged regions, thus forming a refractive index grating 6 and a waveguide. A dielectric layer 8 having a refractive index less than that of lithium niobate is formed above the grating 6 and the waveguide. Electrodes 10 and 12 are formed on opposing faces of the wafer 2 above and below the plane of the grating 6.

A Fabry-Perot semiconductor laser diode 14 having a highly reflecting facet 16 and an anti-reflecting facet 18 has its anti-reflecting facet 18 facing towards the refractive index grating 6 and is optically coupled to the grating 6 by a lens 20. The anti-reflecting facet 18, the surfaces of the lens 20 and the surfaces of the refractive index grating are provided with anti-reflecting coatings.

The laser diode 14 forms a gain medium within a laser cavity. The grating 6 acts as a retro-reflecting grating at one end of the laser cavity. The other end of the cavity is defined by the highly reflecting facet 16. The grating 6 may be controlled to select the wavelength that is reflected back into the cavity and which is then subjected to amplification by the laser diode 14. Thus the diode 14, the lens 20 and the grating 6 cooperate to form a wavelength tunable laser.

During manufacture the wafer 2 is thinned until it is approximately 50 microns thick. A metal mask having openings therein is formed on the surface of the wafer and the wafer is then immersed in an acid bath so

that proton exchange occurs in the unmasked regions of the wafer 2, thereby forming the proton exchanged regions 4.

Suitable patterning of the wafer allows simultaneous formation of the grating 6 and a waveguide. Alternatively optical or electron beam lithographic techniques may be used to form the patterning. Electron beam lithography is more suited to the production of first order gratings where, for a laser operating at a wavelength of 1500nm, the grating period is less than 400nm with feature sizes of less than 200nm.

Application of a time invariant electric field across the grating, due to application of a steady voltage to the electrodes 10 and 12, fixes the output wavelength of light emitted from an output 22 of the apparatus. The line width of the output is typically less than 0.001 Angstroms for a first order grating and less than 0.1 Angstroms for higher order gratings.

In an alternative arrangement, the highly reflecting facet 16 may be arranged to transmit a small proportion of the light impinging thereon, and the transmitted light may be taken as the output of the laser.

The laser diode 14 may be amplitude modulated without chirp, i.e. without frequency shift, and thus the output of the apparatus is suitable for use in coherent communication systems and in wavelength division multiplexing systems using narrow channel spacings. In this latter case, the apparatus may be tuned by application of a suitable DC voltage to the electrodes 10 and 12, such that it can occupy any one of a plurality of channels. This is especially useful in passive optical network systems where the wavelengths of the receivers are fixed and routing is determined by the transmitter wavelength. The electro-optic tunable grating may also be used as an electrically controllable filter for receivers

in a system where the transmitter wavelengths are fixed and the receivers are tuned to match the transmitter. The above options may be combined to provide a fully flexible system. A wavelength division multiplexed optical source may be provided by an array of such laser/grating combinations. Each laser may be individually amplitude or frequency modulated.

Integration of a quasi phase matched second harmonic generator with the tunable grating is possible, thereby providing a second harmonic generator with well defined wavelength control which is immune to temperature fluctuations over a predetermined range. The formation of a quasi phase matched second harmonic generator in Potassium Titanyl/Phosphate (KTP) and a periodic structure acting as a distributed Bragg reflector has been described by W.P.Risk et al (noted above). However, the conditions for quasi phase matching and distributed Bragg reflection are not automatically satisfied over a range of temperatures. The quasi phase matched second harmonic generator region described by Risk et al is formed by periodic domain inversion produced by ion exchange and heating, the difference in refractive index caused by the ion exchange forming a distributed Bragg reflector.

Figure 3 illustrates an apparatus which is similar to that described with reference to Figure 2. However, a further region 30 is formed within the wafer 2. The region 30 comprises a plurality of alternating domains (as indicated by the direction of the arrow within each domain) produced by ion exchange and heating, followed by annealing such that each domain has the same refractive index. Thus the region 30 functions as a quasi phase matched second harmonic generating region but not as a distributed Bragg reflector.

With an electro-optic controlled distributed Bragg reflector and the quasi phase matched second harmonic generating region on the same substrate, the electronically controllable grating can be controlled to compensate for the difference between the change in phase matching wavelength of the quasi phase matched region for a given temperature rise and the change in reflection wavelength of the grating acting as a distributed Bragg reflector for the same temperature rise. For operation with a laser at 1500nm, this gives rise to a requirement to provide electro-optic control of approximately 0.04nm/K or ± 1.2nm for operation at 300 kelvin ± 30 kelvin. This can be achieved by control voltages of ± 1000V across a 50 micron wide wafer.

The refractive index grating may be formed within an optical fibre.

Figure 4 shows an electronically controllable surface emitting grating. The arrangement is similar to that shown in Figure 2. However, the lens 20 and the refractive index grating 6 do not form part of the laser cavity of the laser diode 14 as in Figure 2 but are components which receive the light output of the laser 14. The lens 20 focuses the light from the laser 14 into the refractive index grating 6. Light can be coupled out of the surface of the grating at an angle of θ to the normal.

The angle θ is given by:

$$m\lambda/\Lambda = \sin\theta - n_{eff} \tag{4}$$

where the symbols are as defined hereinbefore.

For $\theta = 45°$, $n_{eff} \approx 2.2$, $m = -2$, $\lambda = 600$nm, a grating pitch of 800nm and an electrically controllable variation in refractive index $\Delta n = 0.0033$, then a

variation in θ of 0.3° is obtainable.

It is thus possible to provide an electronically controllable grating.

Claims:

1. An electrically controllable grating, comprising an electro-optic material having a first region forming a refractive index grating, and means for applying an electric field to the refractive index grating for controlling the refractive index of the electro-optic material.

2. An electrically controllable grating as claimed in Claim 1, in which the means for applying the electric field is arranged to apply a field having a component transverse to the refractive index grating.

3. A grating as claimed in Claim 1 or 2, further comprising first and second electrodes for applying the electric field to the first region.

4. A grating as claimed in any one of the preceding claims, in which the grating is contained within an optical waveguide.

5. A grating as claimed in Claim 4, in which the waveguide is an optical fibre.

6. A grating as claimed in any one of the preceding claims, in which the electro-optic material has a second region which is optically in series with the first region and which comprises a non-linear optical element.

7. A grating as claimed in Claim 6, in which the non-linear optical element is a second harmonic generator.

8. A grating as claimed in Claim 7, in which the second harmonic generator is a quasi-phase matched second harmonic generator.

9. A grating as claimed in Claim 4, in which the second region is contained within an optical waveguide.

10. A grating as claimed in Claim 4 or 9, in which the waveguide comprises a dielectric layer.

11. A grating as claimed in Claim 10, in which the waveguide is cladded by the dielectric layer.

12. A grating as claimed in Claim 10 or 11, in which a first electrode is formed over the dielectric layer in the vicinity of the first region.

13. A grating as claimed in any one of the preceding claims, in which the electro-optic material comprises lithium niobate.

14. A grating as claimed in any one of the preceding claims having at least one end surface coated with an anti-reflecting layer.

15. A surface emitting grating comprising a grating as claimed in any one of Claims 1 to 3.

16. A laser comprising a gain medium and a cavity, one end of which is defined by a grating as claimed in any one of the Claims 1 to 14.

17. A laser as claimed in Claim 16, in which the gain medium is a semiconductor laser diode.

18. A laser as claimed in Claim 16 or 17, further comprising means for amplitude modulating the laser.

9. A grating as claimed in Claim 4, in which the second region is contained within an optical waveguide.

10. A grating as claimed in Claim 4 or 9, in which the waveguide comprises a dielectric layer.

11. A grating as claimed in Claim 10, in which the waveguide is cladded by the dielectric layer.

12. A grating as claimed in Claim 10 or 11, in which a first electrode is formed over the dielectric layer in the vicinity of the first region.

13. A grating as claimed in any one of the preceding claims, in which the electro-optic material comprises lithium niobate.

14. A grating as claimed in any one of the preceding claims having at least one end surface coated with an anti-reflecting layer.

15. A surface emitting grating comprising a grating as claimed in any one of Claims 1 to 3.

16. A laser comprising a gain medium and a cavity, one end of which is defined by a grating as claimed in any one of the Claims 1 to 14.

17. A laser as claimed in Claim 16, in which the gain medium is a semiconductor laser diode.

18. A laser as claimed in Claim 16 or 17, further comprising means for amplitude modulating the laser.

19. A laser as claimed in any one of Claims 16 to 18, further comprising means for superimposing an alternating voltage on a steady voltage for producing an amplitude modulated electric field at the first region so as to wavelength modulate the laser.

20. An array of gratings comprising a plurality of gratings as claimed in any one of Claims 1 to 14.

21. An array as claimed in Claim 20 in which each grating is independently controllable.

22. A wavelength division multiplexed light source comprising an array of lasers as claimed in any one of Claims 16 to 19.

23. A tunable optical filter comprising a grating as claimed in any one of Claims 1 to 9.

Patents Act 1977 **Examiner's report to the Comptroller under Section 17** **(The Search report)**	Application number GB 9401193.9
Relevant Technical Fields (i) UK Cl (Ed.M) G2F (FCE, FCW) (ii) Int Cl (Ed.5) G02F 1/03	Search Examiner G M PITCHMAN Date of completion of Search 14 APRIL 1994
Databases (see below) (i) UK Patent Office collections of GB, EP, WO and US patent specifications. (ii) ONLINE : WPI, CLAIMS	Documents considered relevant following a search in respect of Claims :- 1 TO 23

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P: Document published on or after the declared priority date but before the filing date of the present application.

E: Patent document published on or after, but with priority date earlier than, the filing date of the present application.

&: Member of the same patent family; corresponding document.

Category	Identity of document and relevant passages		Relevant to claim(s)
X	GB 1557484	(XEROX) - see page 2 lines 5 to 26	1
X	GB 1516427	(HAGIWARA) - see page 1 lines 30 to 97	1
X	US 3995937	(BAUES) - see column 3 lines 51 to 65 and column 5 line 56 to column 7 line 47	1, 4

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